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Parameter influence on the laser weld geometry documented by the Matrix Flow Chart

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Abstract

Three variants of fibre laser welding of corner joints where studied. In service a welded piece experiences fatigue load in a complex manner. The peak stress responsible for the fatigue life of the product is mainly determined by positioning and the geometry of the resulting weld. Some top and root shapes where identified for the joints studied. While parameter documentation is straightforward, generalization and combination of knowledge is a challenge. A new documentation method, the Matrix Flow Chart, MFC, turned out to be a powerful solution for large scale documentation, combination and generalization.

Three variants of fibre laser welding of corner joints where studied. The peak stress responsible for the fatigue life of the product is mainly determined by the geometry of the resulting weld. Different top and root shape classes were identified for the joints studied. The shapes mainly depend on geometrical laser beam parameters and govern the peak stress. While parameter documentation used to be straightforward, generalization and combination of knowledge is a challenge. A new documentation method, the Matrix Flow Chart, MFC, turned out to be a promising solution for large scale documentation.

Keywords: laser; weld; join; geometry; parameter; knowledge

1. Introduction

In present paper, three variants of laser welded corner joints are studied, in order to find the most suitable one to apply for a beamer. In service, the beamer will experience fatigue load in a complex manner. How the weld will perform is mainly determined by the geometry of the resulting weld, beside the weld throat depth as a main criterion.

1.1. Welding quality

The quality of laser welds is characterized by superior abilities compared to conventional welding (e.g. resistance spot or electric arc welding), abilities that enable high precision and high quality of the corresponding product. It is

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unfortunately held back by high investment costs and difficulties of achieving quality in a robust manner. The process window is often narrow and has physical mechanisms that are not fully understood. The quality of a weld can be regarded from two sides of view. A welded product in service has to resist load conditions, where poor weld quality can cause fracture [1, 2]. During manufacturing, the chosen parameters determine the welding process which in turn determines the weld quality. Additionally, laser welding is an enabler for welding (ultra) high strength steels with different grades. Due to high welding speed and narrow interaction zone, the laser welding process creates a narrow HAZ, often without softening. The new high brilliance lasers (fibre, disc) have excellent beam properties, but can produce violent evaporation and spatter, which needs to be eliminated.

Essential for the mechanical properties of a weld under load, besides the metallurgical properties, is its geometry, especially the top and root shape. In order to achieve a good weld quality that can handle the loading situations a weld will have to endure, thus different welding defects have to be suppressed. The standards [3] define acceptable weld properties, but are unsatisfactory since the knowledge for load situations is not enough generalized. The shape of laser welds has been studied [4], but not in a context between publications that is systematic and generalized. Weld cross-section shapes can depend on the pool geometry and type of shielding gas [5]. Spiking can disrupt the root shape for the new high brightness lasers (fibre, disc) [6]. Simulations concerning the cross-section weld shape have also been made [7].

For fatigue bending load, either the top or the root often is under compression and is thus uncritical [1]. The other side of the weld is then under tensile forces that enable fatigue crack initiation and propagation, governed by the shape of the weld. An overview of fatigue analysis of welds is given in [8] and fatigue properties and cracking behaviour in [9, 10].

1.2. Knowledge transfer

Despite the large number of experiments from case studies and applications of welding (including laser welding) made in the past, the knowledge transfer to other applications is difficult. Each parameter set is different and it is difficult to see that one parameter in the e.g. 20-dimensional space learns from another. Inspiration from other subjects could be attained, for example in machining where a management information system was developed [11]. However, the treatment of abstract data such as parameter combination in a multidimensional space is rare and strategies are not apparent. Increased treatment and visualization of data depends on the human cognitive ability and disability [12]. Knowledge transfer visualization, perception and cognition is in welding barely mentioned, but can be the key for solving how knowledge can be transferred in a new and more efficient manner. One method to illustrate, generalize and standardize the documentation of findings is the Bifurcation Flow Chart (BFC) [13, 14].

2. Method

2.1. Methodological approach

For the three chosen weld situations process parameters where varied in a selective manner to keep the number of experiments limited, and yet systematic. The resulting weld cross sections were commonly arranged in a comparable manner, meant to be suitable for predicting trends of shapes in the chosen parameter vicinity. The top and root shapes are of great importance as possible stress raisers when the welded beamer will be put under load. Therefore typical weld shapes were identified and categorized, including the definition of the key dimensions. The trends of weld shapes and of possible defects can be derived from the parameter variations. Comprehensive Finite Element (FE) stress analysis has been conducted for different joints and weld shapes [1]. The impact of the top and root shapes and differences of different joint types are presented from selected results. This is of great value if the main findings are transferred to similar geometries.

After the findings are discussed and conclusions are drawn, additional documentation is made by applying the Matrix Flow Chart (called MFC, in frame of the present study developed by the authors) for all the trends found from the experimental results, creating a systematic core of results that hopefully are easier to track, discuss, to refer to and to extend.

2.2. Experimental set-up

The joints under investigation are an eccentric corner joint with 6 mm interface having full penetration (case A), see Fig. 1(b) (published earlier in more detail [15, 16]) and a butt joint with 15 mm joint for both 6 mm partial (case B) and 15 mm full penetration (case C), see Fig. 1(c). All three cases have the aim to make a support beamer consisting of four equal welds, Fig. 1(a), where the top plate is lowered for case B and C compared to case A. Each joint type studied has particular advantages, particularly with respect to outer geometry, load and root control. Both plates are made of high strength steel of different grades (15 mm: Weldox 960, 6 mm: Domex 700) and are laser cut at the edges, enabling close-to-zero gap before welding (the remaining oxide layers where not removed). Fig. 1(d) is an illustration of the long-section of the melt pool and of the keyhole during welding [17].

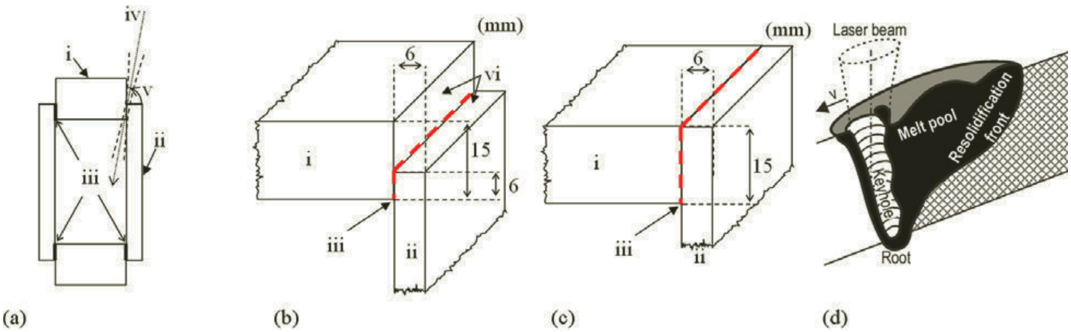


Fig. 1. (a) Cross section of the beamer, here with (b) an eccentric corner joint. (c) butt joint as an alternative (d) 3D-illustration of the melt pool in laser keyhole welding (here: butt joint) [Legend: (i) HS-steel Weldox 960, (ii) HS-steel Domex 700, (iii) joint to be welded, (iv) laser beam axis, (v) beam inclination angle, (vi) laser cut surfaces]

The process parameters varied during the experiments are the welding speed v and laser power P. The laser alignment parameters changed are beam inclination angle α, focal plane position z_0, and lateral offset y. All other parameters are fixed as follows: laser type: Yb:fibre laser YLR-15000 (IPG Laser, maximum beam power: 15 kW cw), output fibre diameter: 200 µm, Beam Parameter Product (beam quality) 10,4 mm·mrad, wavelength: 1070 nm.

The optics (2 lenses) chosen is: collimator length 150 mm, focal length: 500 mm, resulting magnification M=3,3. Accordingly, the projected fibre end results in a focal spot diameter of 0,67 mm and a Rayleigh length (depth of focus) of ± 8 mm. The longest among five focal lengths was chosen, to provide a sufficiently long Rayleigh length compared to the penetration depth for all three cases.

Shielding gas: Argon, gas flow rate: 20 liters/min, through a nozzle near and aimed at the weld (top side).

Some of the welding experiments were accompanied by high speed imaging for additional analysis [15,16].

2.3. Evaluation

The resulting welds are etched and later photographed under an optical microscope. The shapes, including possible defects, were judged and classified. For this purpose suitable classification definitions were developed, including essential shape dimensions that were measured. For the different joint types and weld shapes, a comprehensive stress analysis was carried out with Finite Element (FE) analysis, from which the maximum stress per joint and root type was computed, published in separate papers [1]. Some few results are given just to illustrate the basic trends.

2.4. Documentation by the Matrix Flow Chart

As mentioned earlier, the transferability of research results is a basic problem in welding. There is no certainty that findings from one case study with its set of parameters are applicable for another case and operating point. A solution for eliminating welding defects may yet be transferable. Instead of having numerical parameter values, guidelines and trend rules can be a solution. However, their validity range might not be obvious. Standardized formats and categories are missing through which knowledge could be combined and extended [15].

One step towards the goal of achieving better documentation of the process mechanisms for suppressing or not suppressing a welding defect is the Bifurcation Flow Chart (BFC) [13, 14]. The BFC can combine different findings, enabling tracking of knowledge and conclusions from a common view. It is suitable to compare for a sequence of mechanisms why in one parameter case A certain defect is suppressed that takes place in another case. In the present study, many different input- and output-properties (parameter in, weld quality out) are compared. As the BFC is not suitable for such situation, the Matrix Flow Chart (MFC) has been developed. It is a lucid conceivable, generalized and fairly easy to understand. It contains rules for what can be expected when different parameters changes. Such a table may initially need knowledge/experience from weld results, but may help transferring of knowledge from one case and application to another. The MFC is a kind of black box variant of the BFC, but with parallel rather than sequential nature.

3. Results

In the following the experimental results are presented.

3.1. Cross sections

Figure 2 shows the cross sections of the resulting welds, arranged according to the parameter changes, to support the perception of trends. Figure 2(a) shows the welds for the eccentric corner joint (case A), where the parameters varied are: welding speed v, laser inclination angle α, lateral offset y and focal position z_0. Figure 2(b) and (c) (case B and C, respectively) show cross sections of the butt-joint configuration (with a corner at the root side). Figure 2(b) has parameters varied: welding speed v, laser power P and focal position z_0. Figure 2(c)'s cross sections are placed according to the line energy P/v, divided into for vertical lines, where the first line changes the laser power P at a given focal position and speed. The second and third line show results of speed changes at two different laser power levels, 5 kW and 15 kW respectively. The fourth line also shows the speed change at 15 kW, but at a lower focal plane position, -9 mm.

3.2. Shape identification and trends

From the cross sections in Fig. 2, five different corner top and corner root shape classes where identified for an eccentric corner joint, shown in Fig. 3(a) and (b). In Fig. 3(c) the six flat top shape classes identified are shown, derived from the results in Fig. 2. The root shapes for partial penetration end up in a notch-like situation. This case as a function of the gap width was studied for hybrid welds (CO_2-laser + MIG) previously [18]. In the simulations zero gap was compared with rounded roots then. Figure 3(d) shows the standard [3] laser welding defects accompanied by possible reasons for them.

Figure 4 shows how the shapes and categories change for varying parameters according to Fig. 2, using the same layout. Figures 4(a) and (b) show the corner top and root class changes while Fig. 4(c) and (d) show the flat top class change according to the layout in Fig. 2(b) and (c) respectively.

3.3. Stress Analysis

From the Finite Element stress analysis (the load being simplified by a slightly inclined force at the left upper beamer corner), described in more detail in [1], the following is concluded for the three cases, shown in Fig. 5. For the present fatigue load direction the root is more critical for stress raising [15]. Case A enables to control the root, as does Case C, but by overdimensioning the penetration depth (15 mm, the 6 mm side wall then determines the peak stress), while Case B with partial penetration forces a notch-root, which is unfavourable and perhaps needs gap preparation.

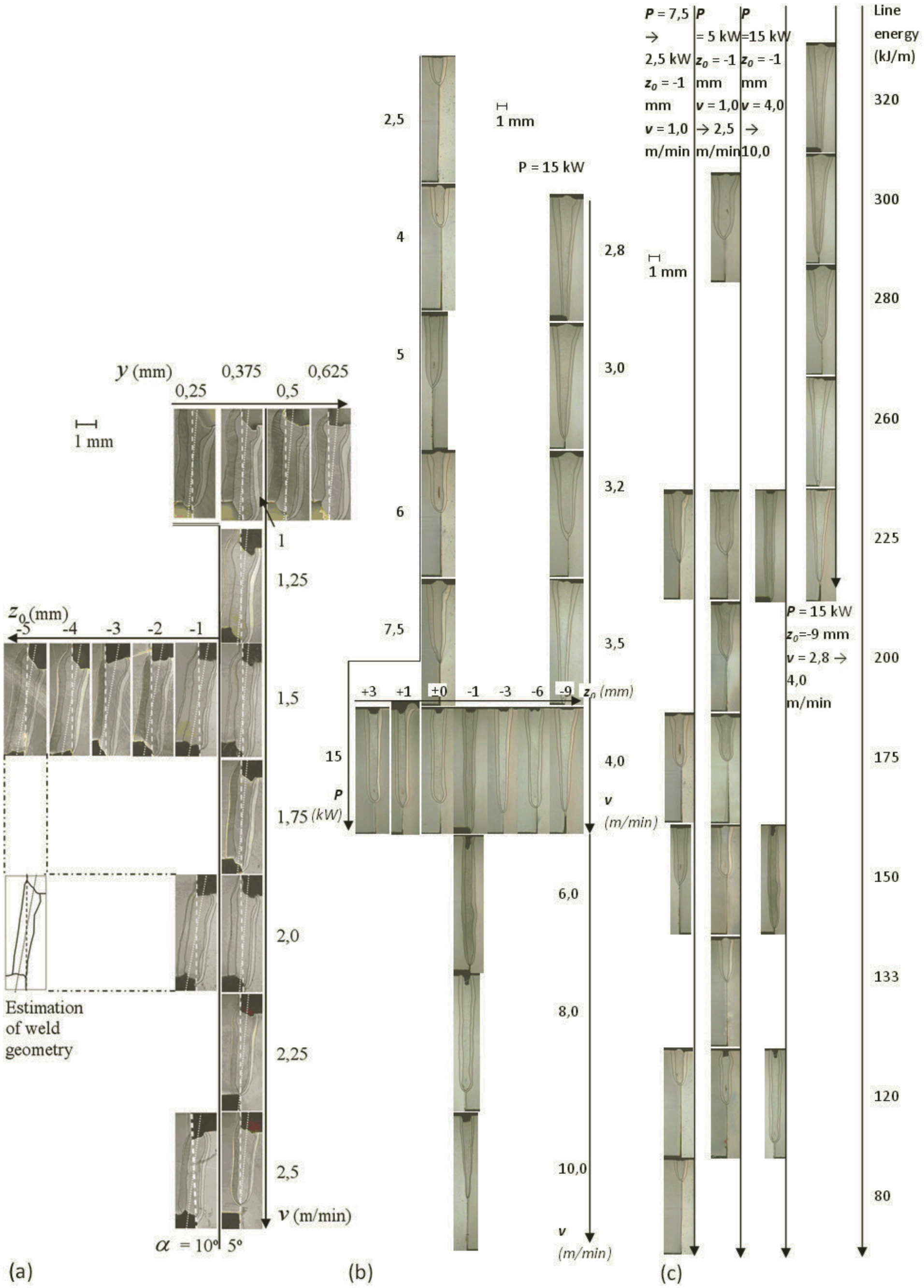


Fig. 2. Weld cross sections (a) case A (5 mm eccentric corner joint), slashed line: joint interface, dotted line: laser beam axis, (b), (c) case B (butt joint, aiming at 6 mm penetration) and case C (butt joint, aiming at full 15 mm penetration) [note the different scale of (a) to (b),(c)]

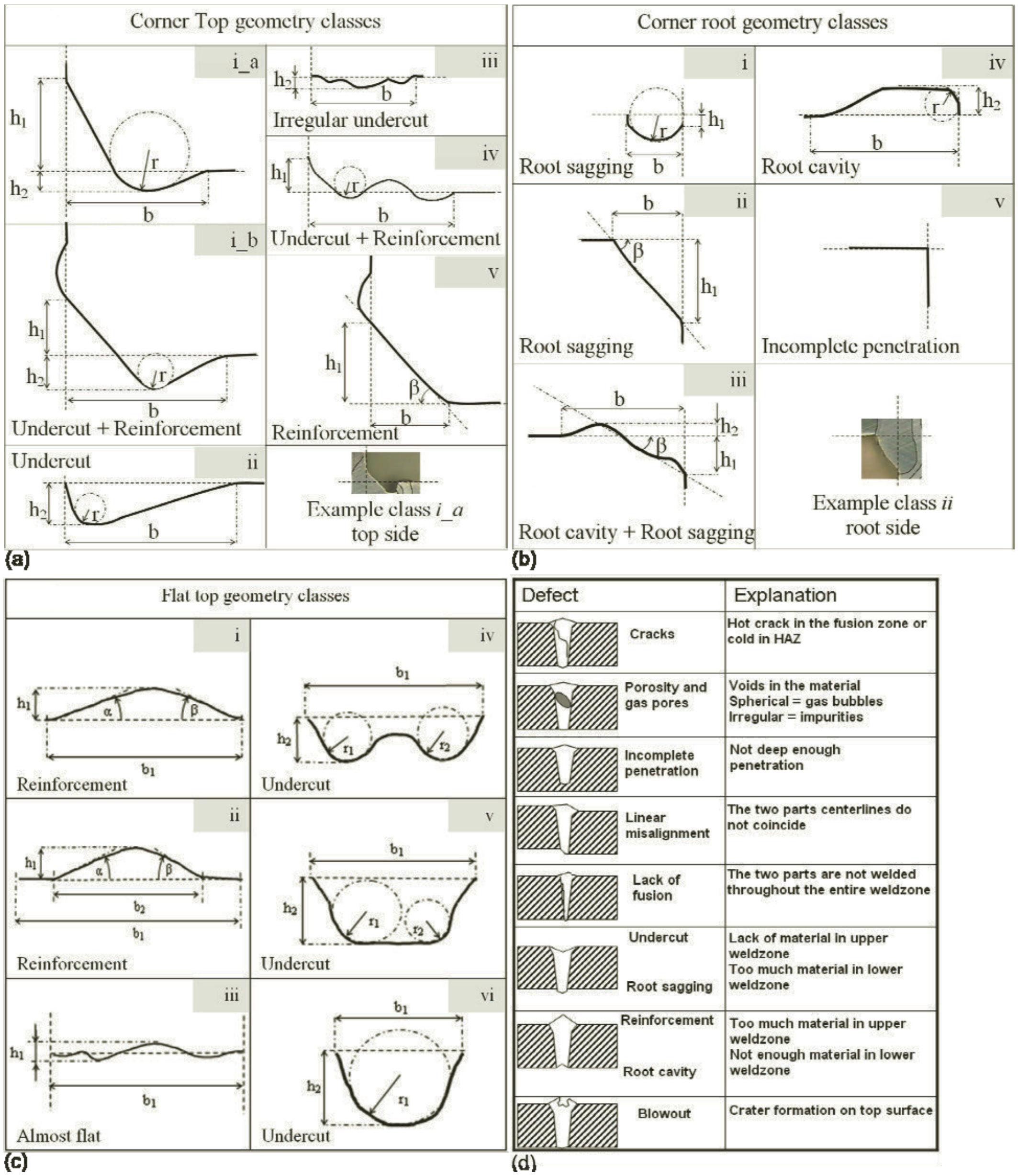


Fig. 3. Geometry classes defined: (a) *corner top*, (b) *corner root*, (c) *flat top;* (d) standard [3] laser welding defects

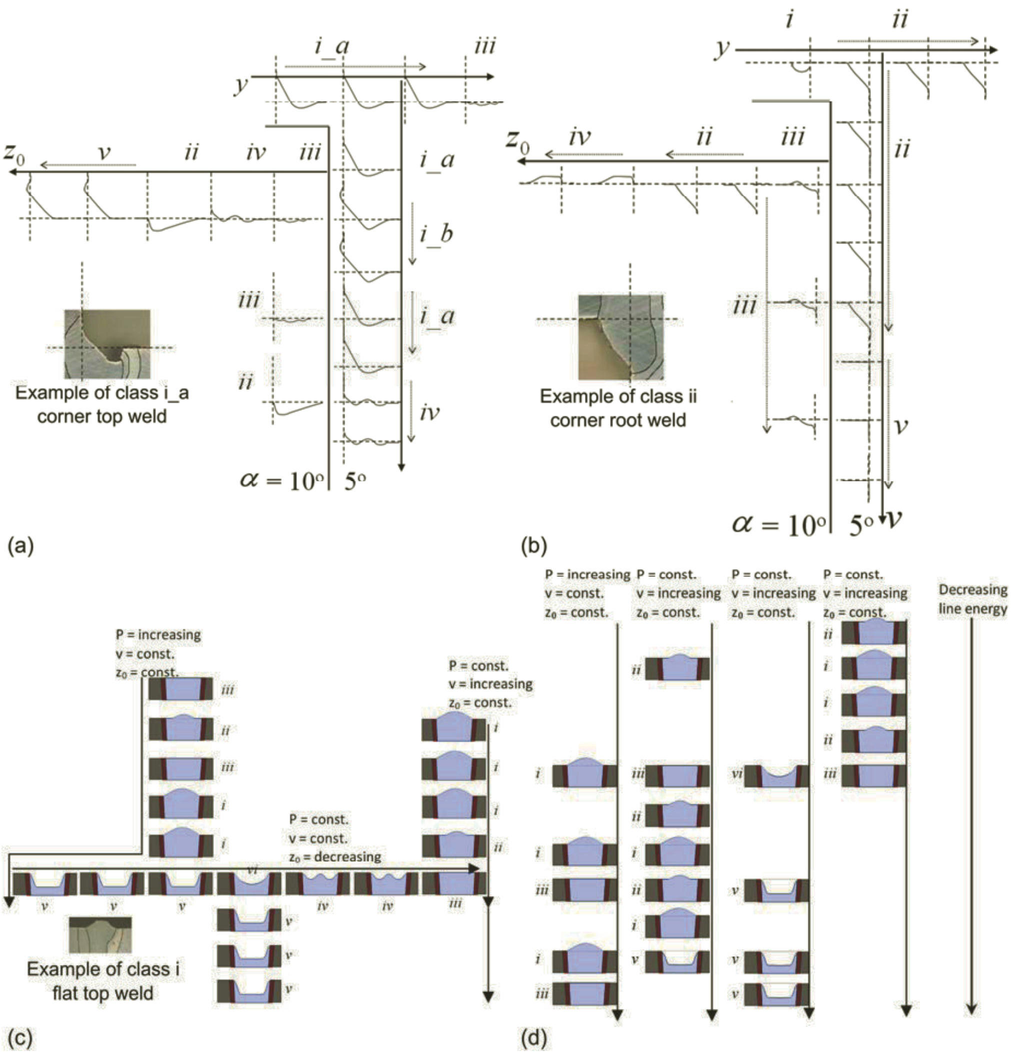


Fig. 4. Weld geometry and its class changes along with the welding parameter changes: (a) corner top, (b) corner root, (c), (d) flat top

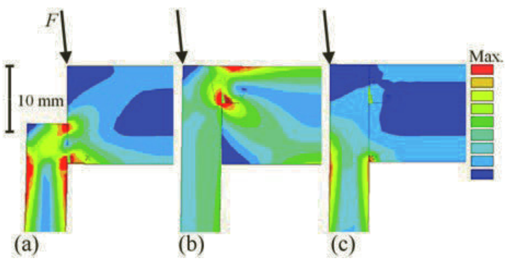
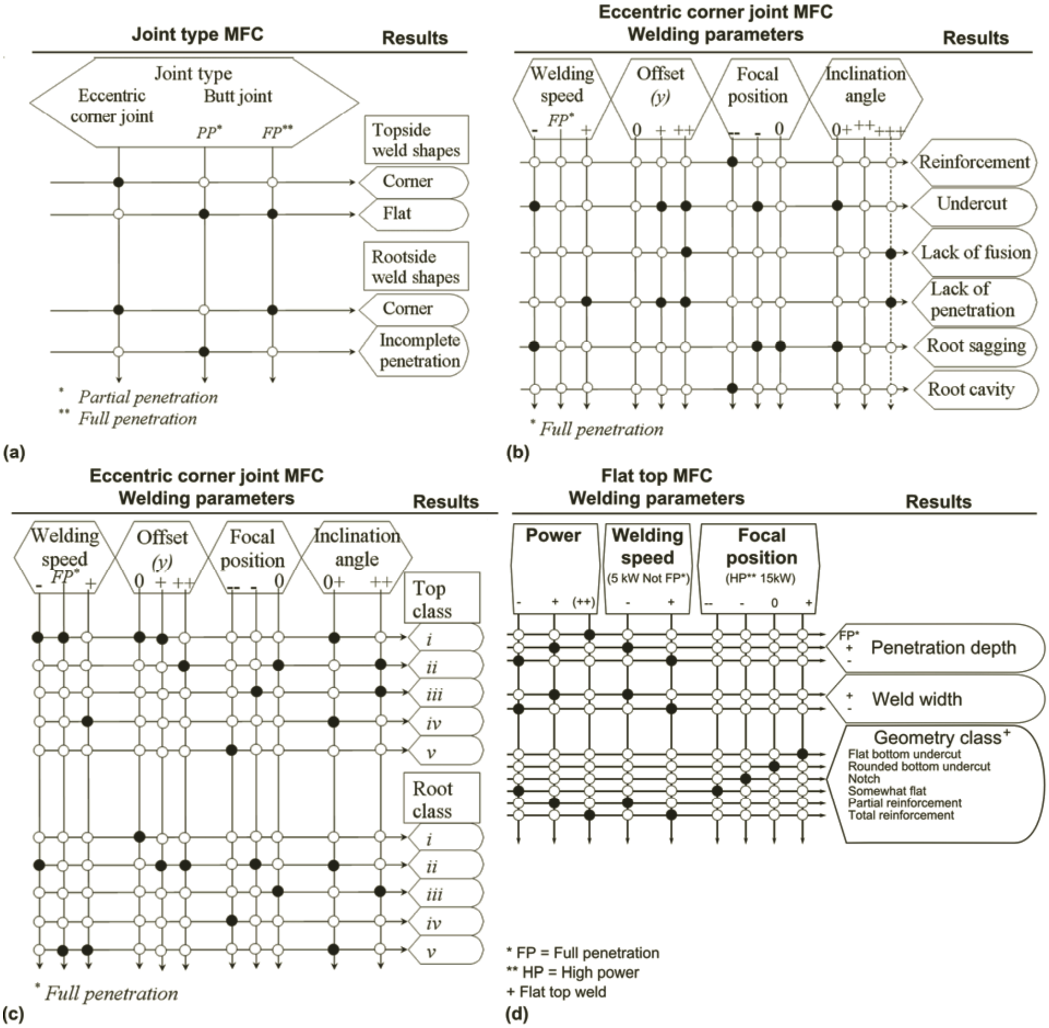


Fig. 5. Calculated stress field (von Mises stress, load F) for three joint types under load *F*: (a) case A, (b) case B (6 mm) (c) case C (15 mm)


Joint type MFC
Results
Joint type
Eccentric corner joint
Butt joint
PP*
FP**
Topside weld shapes
Corner
Flat
Rootside weld shapes
Corner
Incomplete penetration
* Partial penetration
** Full penetration
(a)
Eccentric corner joint MFC
Welding parameters
Results
Welding speed
FP*
Offset (y)
Focal position
Inclination angle
Reinforcement
Undercut
Lack of fusion
Lack of penetration
Root sagging
Root cavity
* Full penetration
(b)
Eccentric corner joint MFC
Welding parameters
Results
Welding speed
Offset (y)
Focal position
Inclination angle
Top class
Root class
* Full penetration
(c)
Flat top MFC
Welding parameters
Results
Power
Welding speed
(5 kW Not FP*)
Focal position
(HP** 15kW)
Penetration depth
Weld width
Geometry class+
Flat bottom undercut
Rounded bottom undercut
Notch
Somewhat flat
Partial reinforcement
Total reinforcement
* FP = Full penetration
** HP = High power
+ Flat top weld
(d)

From the results and reasoning of anchors, the recommended shapes concerning weld durability are (left to right):

- Corner top: *v, iv, iii, i_a, i_b, ii*
- Corner root: *ii, iii, iv, i, v*
- Flat top: *i, ii, iii, v, iv, vi*

Note that sometimes specific shapes like a slight undercut may be desired, if e.g. to keep geometrical tolerances (reinforcement not permitted). Also, the recommendations strongly depend on the transition from the base material to the weld shape.

4. MFC documentation

The trends identified from experiments are documented with the new Matrix Flow Chart (MFC). Figure 8(a) shows how the kind of top and root geometry changes according to joint according to the three Cases A,B,C, while Figs. 8(b), (c) and (d) show according to Figs. 2, 3 and 4 the weld quality and weld shape changes with parameter changes. Note that "OR"-logics is applied and that each point corresponds to at least one experimental evidence, but the limits of generalization of each guideline are not explored yet.

For example, when the focal plane position is varied into the work piece (for top corner joint), the defects undercut and root sagging occur. This is visualized by black circle connection in Fig. 8(b). A white circle means "no connection". These trends may be valid in a more general manner which can be extended and proven by other experts. When a sample has the defects undercut and root sagging, they can be suppressed by increasing the speed or by changing the laser inclination angle. This is the case because both of the parameters caused the defects in one state and none in the other.

The applicability and extension of the MFC has to be proven and further studied in future publications, incorporating results from the scientific community into the present MFC.

5. Conclusions

The following conclusions can be drawn:

(i) Improved documentation and generalization of knowledge is desired, e.g. for transferring welding results systematically; multidimensional and graphical result arrangement facilitates the recognition of trends.

(ii) When varying laser beam parameters, 5 top and 5 root geometry classes for an eccentric corner joint and 6 top geometry classes for a butt joint where identified.

(iii) By carefully planning the placement of a weld and selecting a proper weld shape, stress forces on the weld may be decreased.

(iv) Formulation of trends in the MFC can be a starting point for generalizing gradual identifications of parameter limits and also serve as a guideline for eliminating welding defects.

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